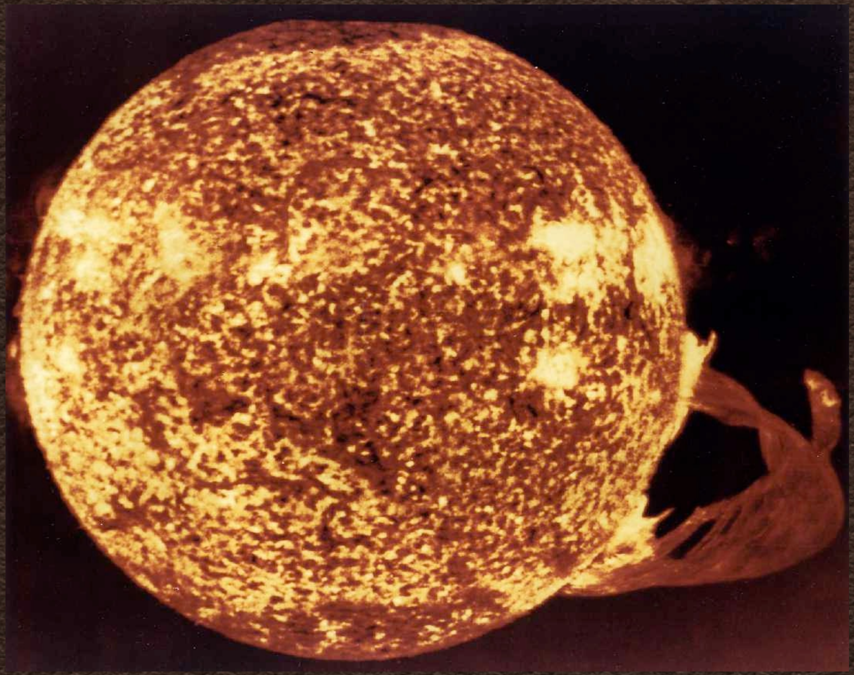
Solar Neutrinos



BULLETIN BOARD

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Solar Neutrinos Are Counted At Brookhaven

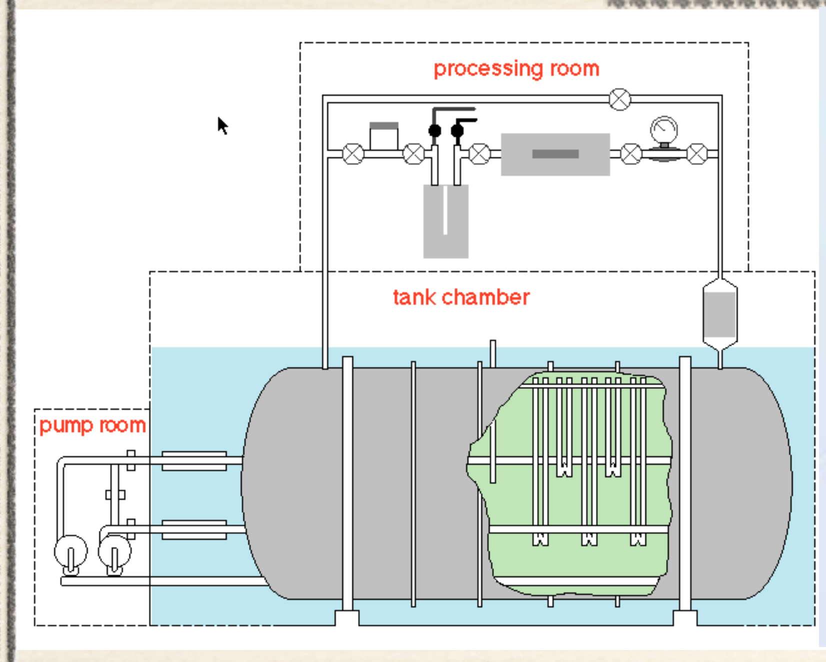
in low level counting experiments. Originally the gun barrels were procured from surplus, and brought to BNL for conversion to more peaceful uses. The long guns were cut into 8-foot sections, weighing about 16,000 pounds each. These guns are made from "old" iron (before the use of atom and hydrogen bombs) and contain a very small amount of residual radioactivity.

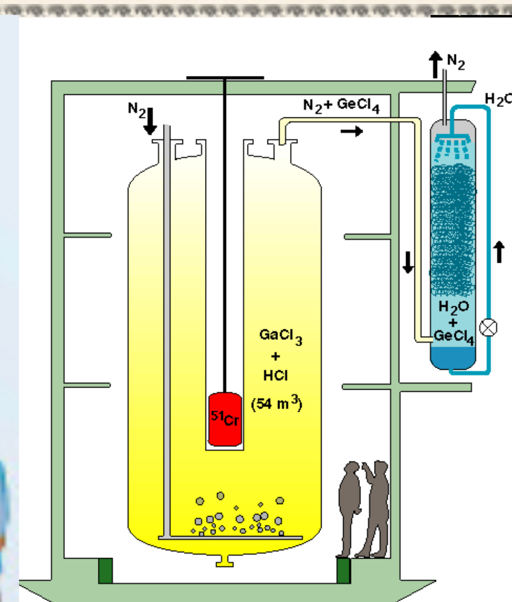
For accurate results, it is necessary to reduce the background radiation to as low a level as possible. Hence, the tank was placed deep underground to shield it from cosmic radiation and the counter was mounted in the thick gun barrel, which acts as a shield. Additional precautions, however, are taken to eliminate interferences from unrelated nuclear processes that could also produce Argon-37 in the tank and possibly result in a false neutrino reading.

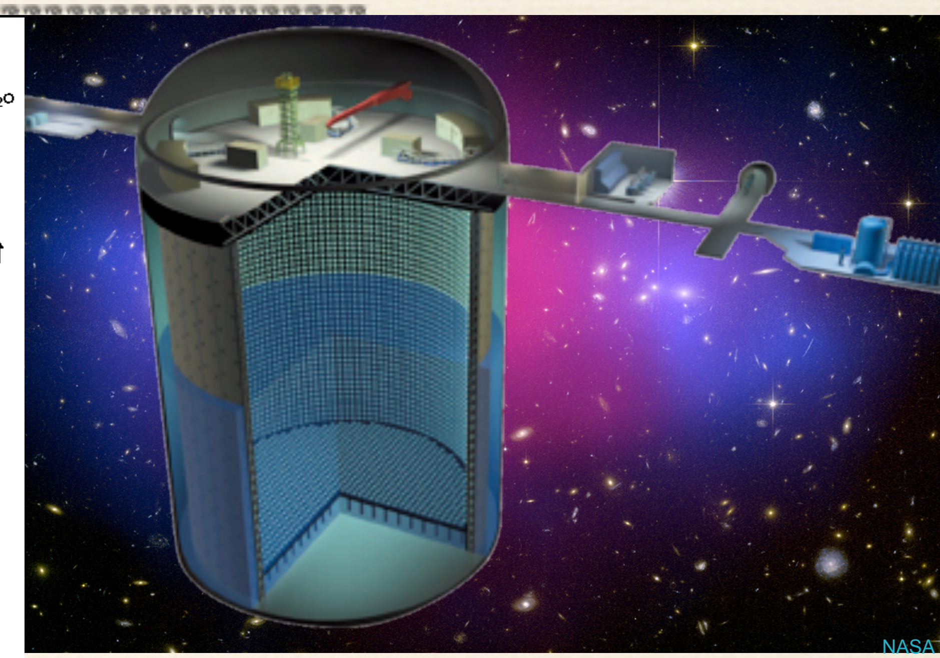
Various elements, when they decay, are capable of producing neutrinos, but there is a definite energy level for each neutrino, and chemists use this method of identifying the neutrino source. In the Brookhaven ex-

WINP at BNL February 5th, 2015 Michael Smy

Past and Present Solar Experiments

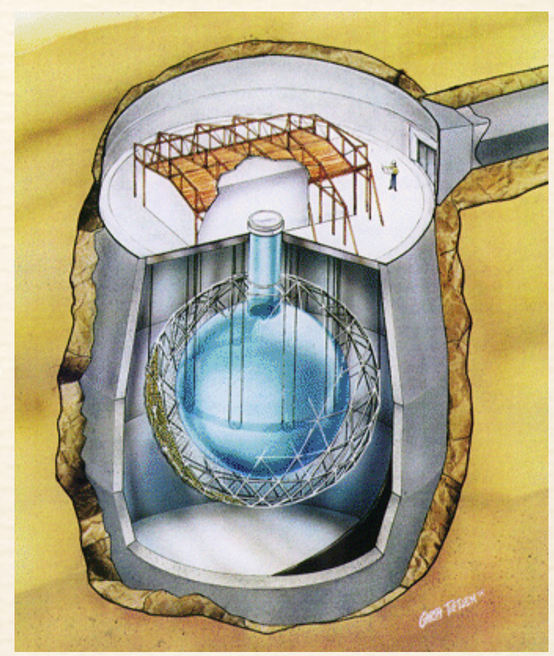
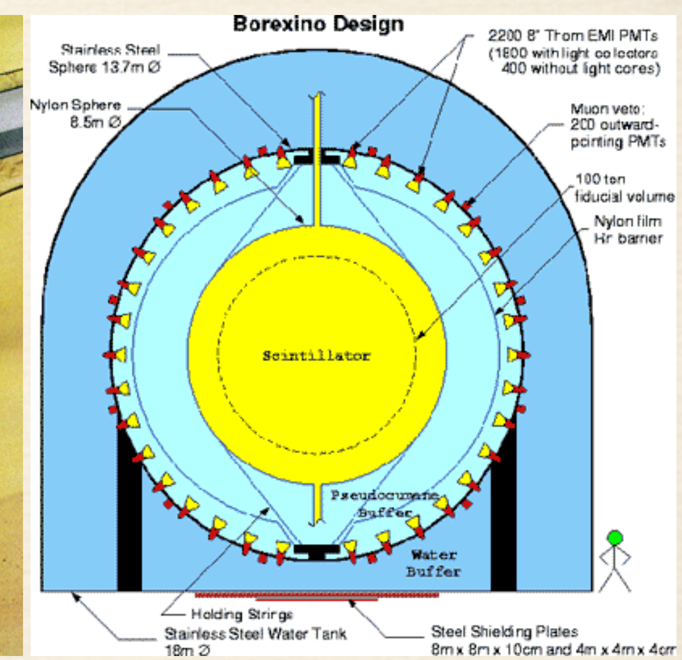






Homestake (Cl) SAGE (Ga) GALLEX(Ga) Super-Kamiokande (H_2O)

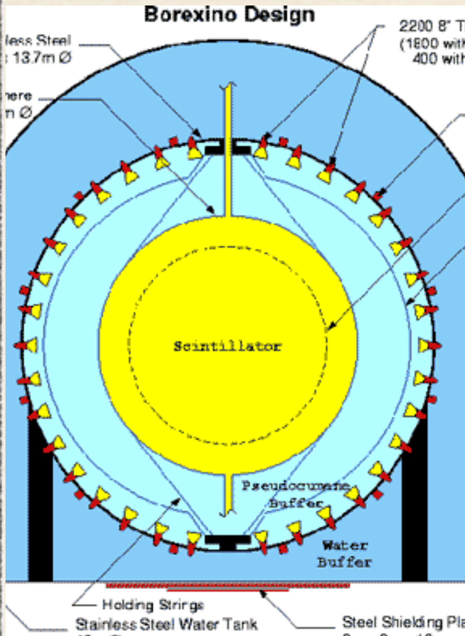
- Radiochemical Detection: Cl➤Ar (>800keV) and Ga➤Ge (>200keV) charged-current interactions (ν_e only)
- water-Cherenkov (>few MeV) e^- elastic scattering, charged-current, neutral-current interactions (all active ν)
- scintillator (>few 100 keV) e^- elastic scattering (all active ν)

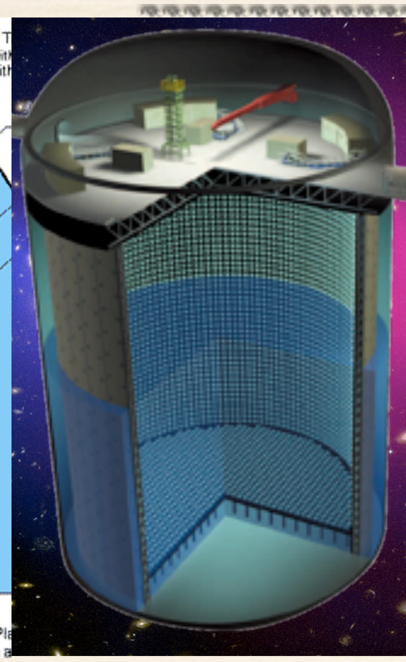
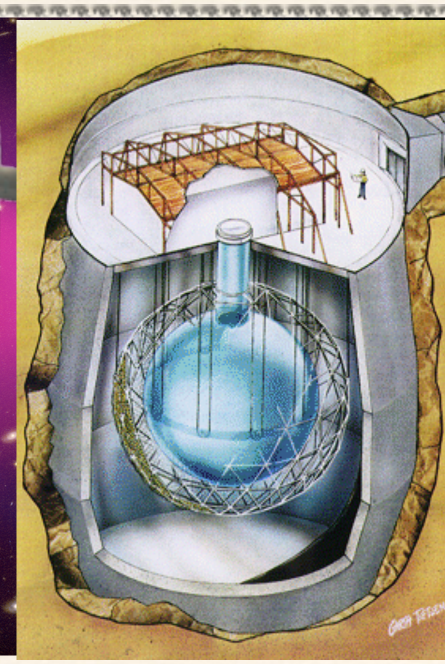
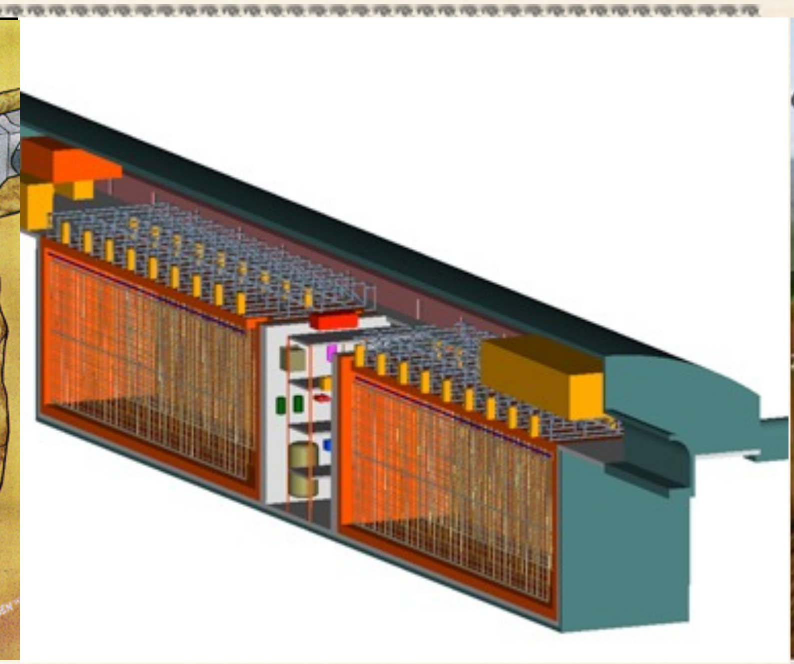
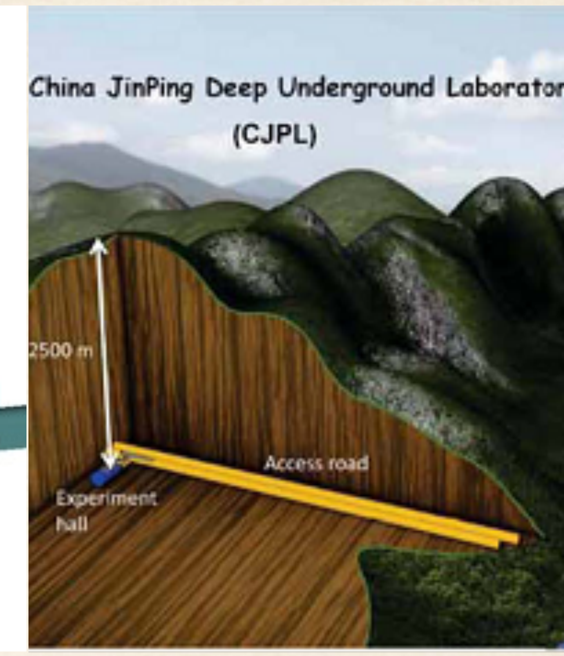



SNO (D_2O) BOREXINO (Scint.)

Michael Smy, UC Irvine

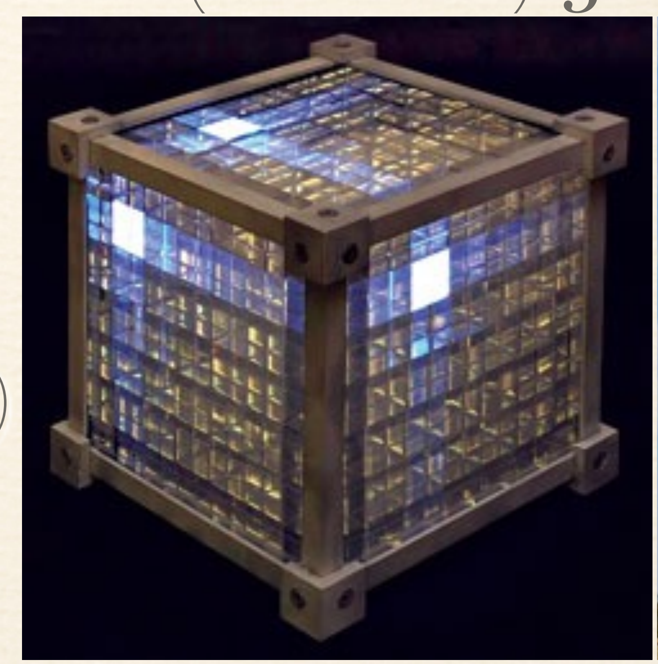
Future Solar Experiments



BOREXINO Super-K SNO+ (Scint.) ELBNF (LArTPC) JinPing (H_2O/Sc)

- liquid Argon TPC: Ar➤K (>few MeV) charged-current interactions (ν_e only)
- loaded scintillator: In➤Sn (>few 100eV) charged-current interactions (ν_e only)
- salt water: Li➤Be (>MeV) charged-current interactions (ν_e only)

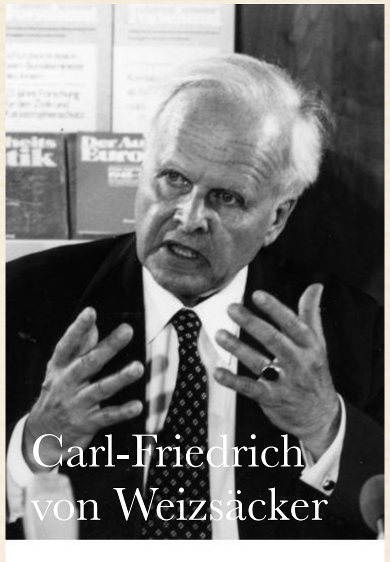


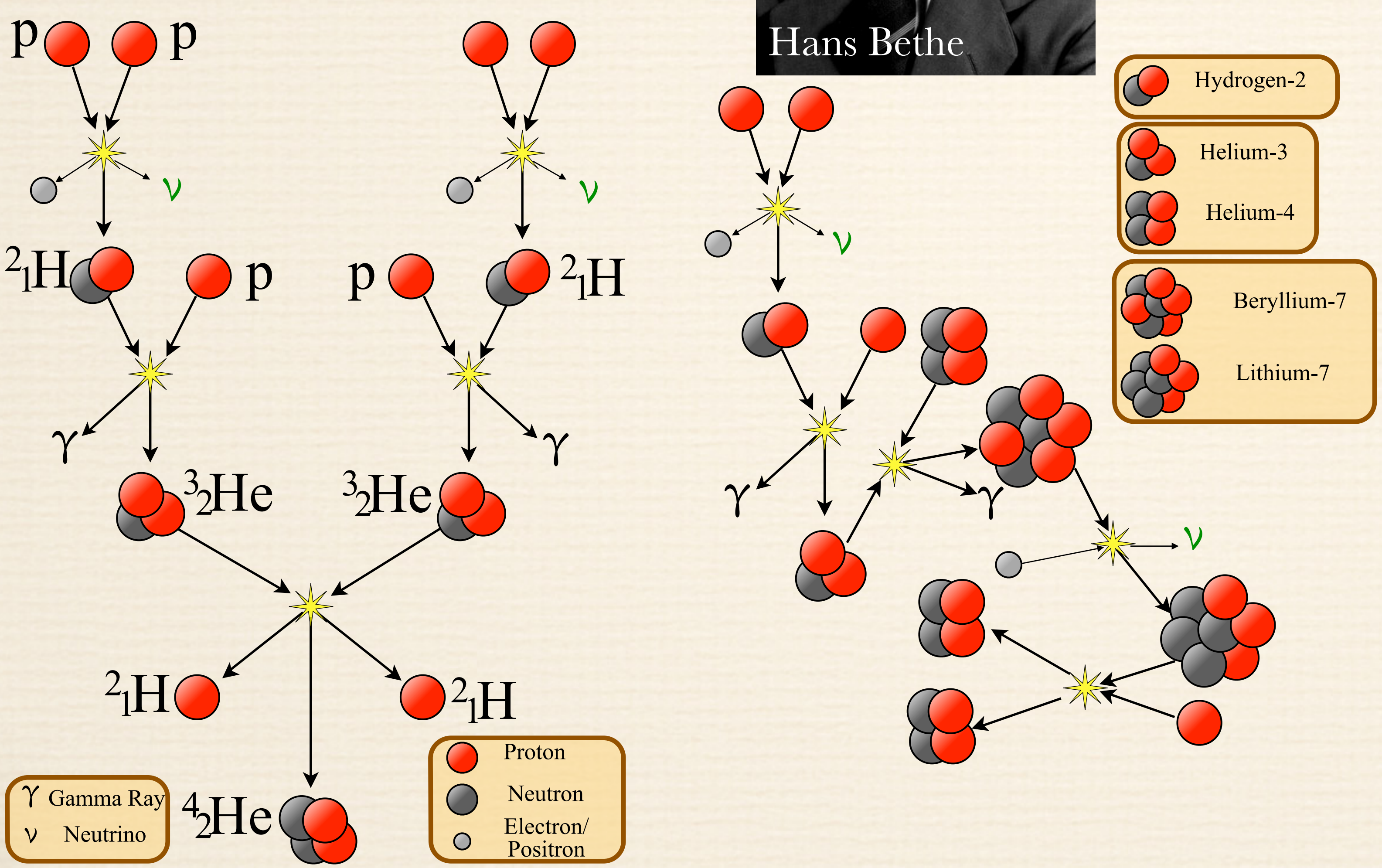

LENS (loaded scint.) Theia (Salt-H_2O)

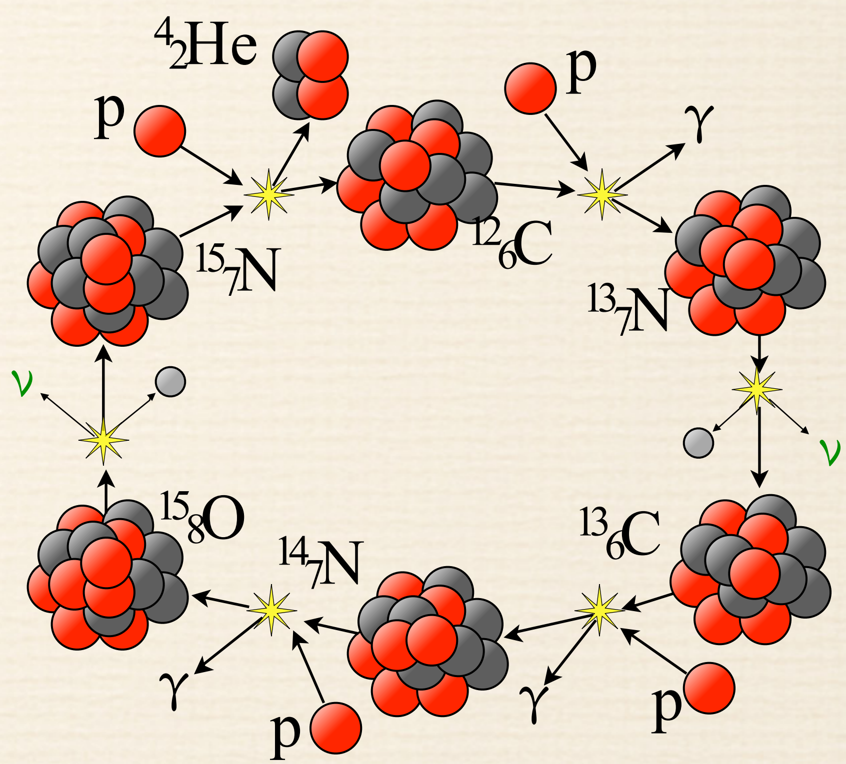
Stellar Energy Production (H-fusion)

pp-chain

CNO-cycle







Solar Neutrino Spectrum

$p+p \rightarrow d+e^{+}+\nu_e$ (99.77%)

$p+e^{-}+p \rightarrow d+\nu_e$ (0.23%)

$d+p \rightarrow {}^{3}He+\gamma$

${}^{3}He+\alpha \rightarrow {}^{7}Be+\gamma$ 15.08%

${}^{3}He+{}^{3}He \rightarrow \alpha+2p$ 84.92%

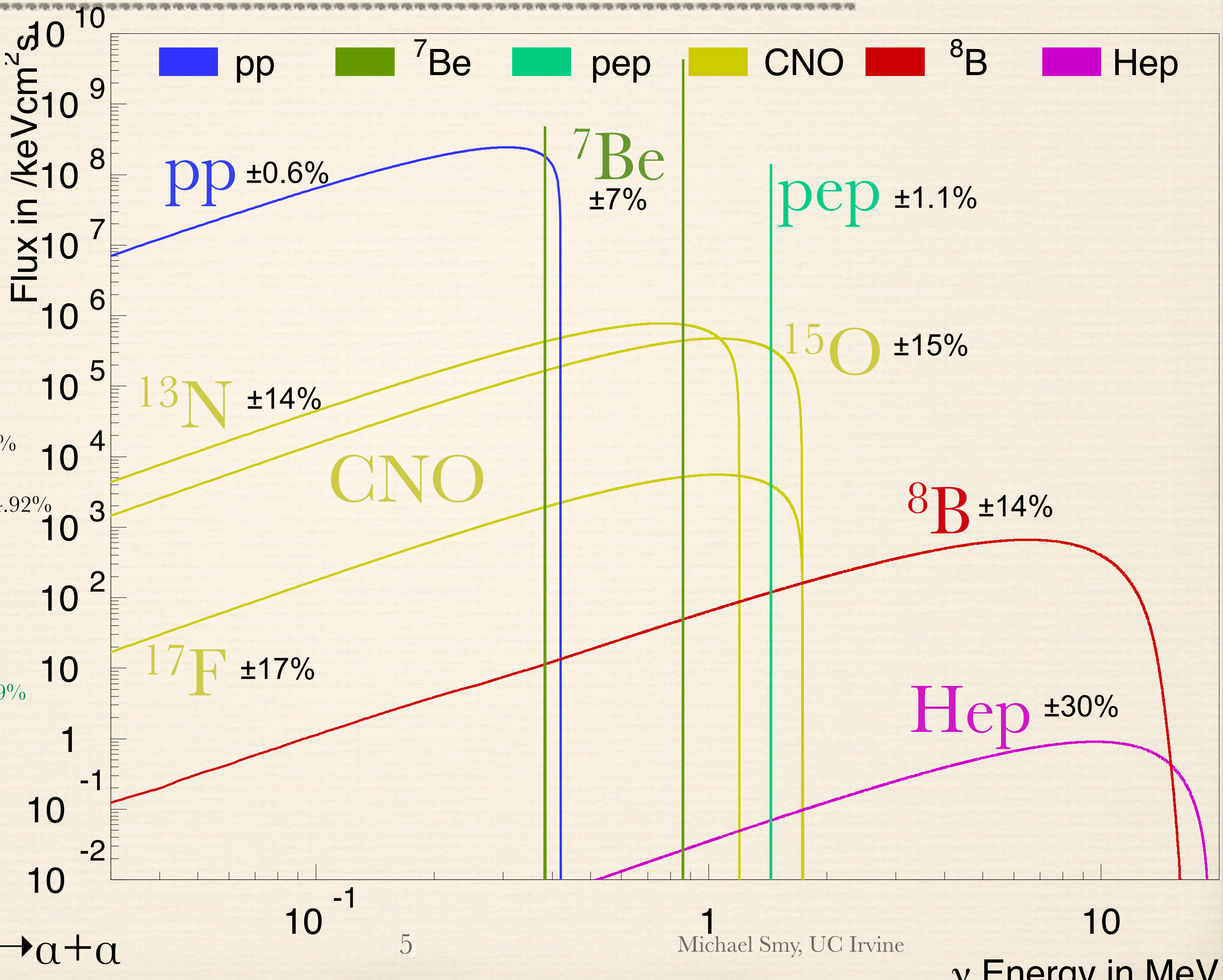
${}^{3}He+p \rightarrow \alpha+e^{+}+\nu_e$

${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$ 99.9%

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$ 0.1%

${}^{8}B+ \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$

${}^{7}Li+p \rightarrow \alpha+\alpha$; ${}^{8}Be^{*} \rightarrow \alpha+\alpha$

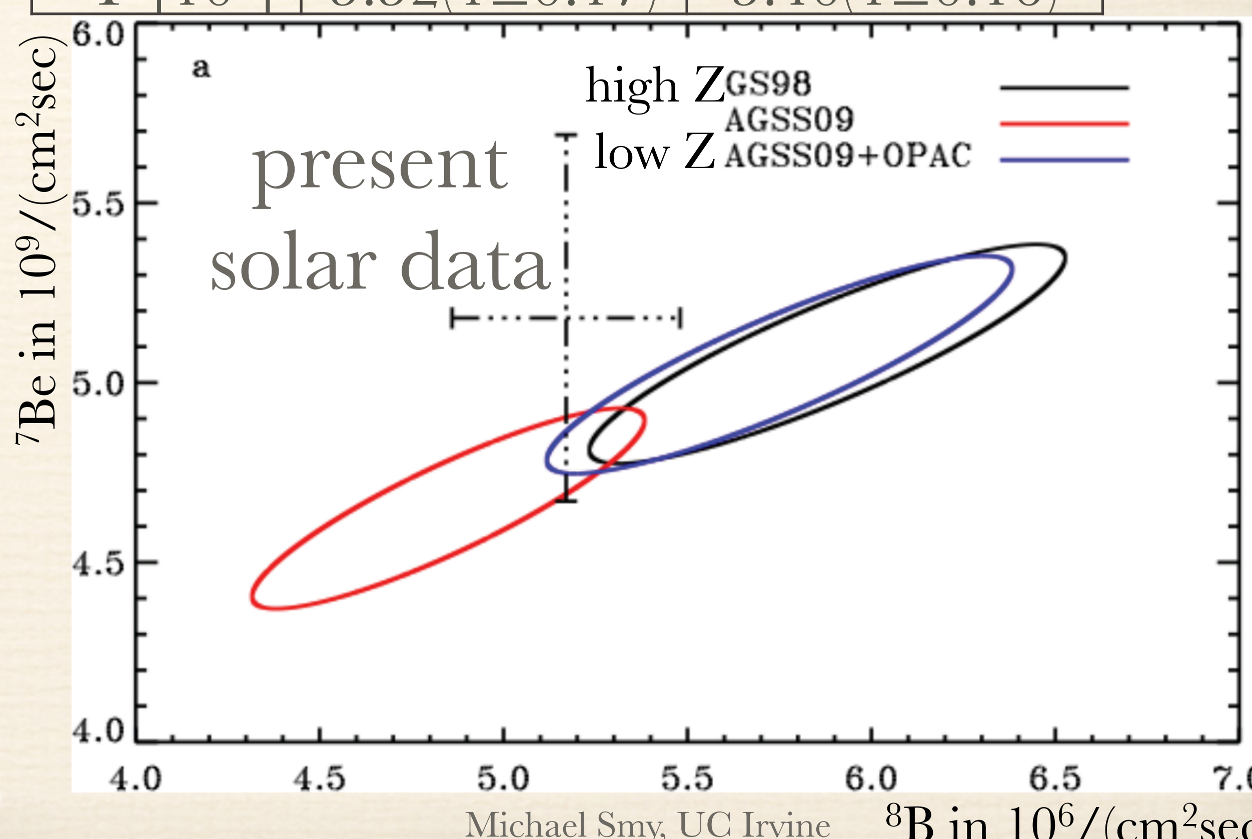


Solar ν's and Element Abundances

- nicely discussed by Serenelli in Kyoto (ν 2012)… not really much changed
- two sets of element abundances: Grevesse & Sauval (1998; GS98) and Asplund et al. (2009; AGSS09), newer AGSS09 doesn't fit as well with helio-seismology data
- AGSS09 reduces CNO flux by ~30%
- changes opacity and core temperature

ν flux	SFII-GS98	SFII-AGSS09	
pp [10^{10}]	5.98(1±0.006)	6.04(1±0.006)	
pep [10^8]	1.44(1±0.011)	1.47(1±0.012)	
hep [10^3]	8.04(1±0.30)	8.31(1±0.30)	
^{7}Be [10^9]	5.00(1±0.07)	4.56(1±0.07)	~10%
^{8}B [10^6]	5.58(1±0.14)	4.59(1±0.14)	~20%
^{13}N [10^8]	2.96(1±0.14)	2.17(1±0.14)	~30%
^{15}O [10^8]	2.23(1±0.15)	1.56(1±0.15)	~31%
^{17}F [10^6]	5.52(1±0.17)	3.40(1±0.16)	~35%

elements	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.93
Si	7.56	7.53
Si	7.56	7.51
Ar	6.4	6.4
Fe	7.50	7.45
Z/X	0.0229	0.0178



Must Measure Solar CNO Neutrinos!

- directly address metallicity issue in solar models
- understand how many stars shine (in many stars, CNO dominates, not pp)
- first shot: BOREXINO (near-term)
- also: SNO+, (medium-term), JinPing, LENS, Theia (long-term)

Particle Physics with Solar Neutrinos

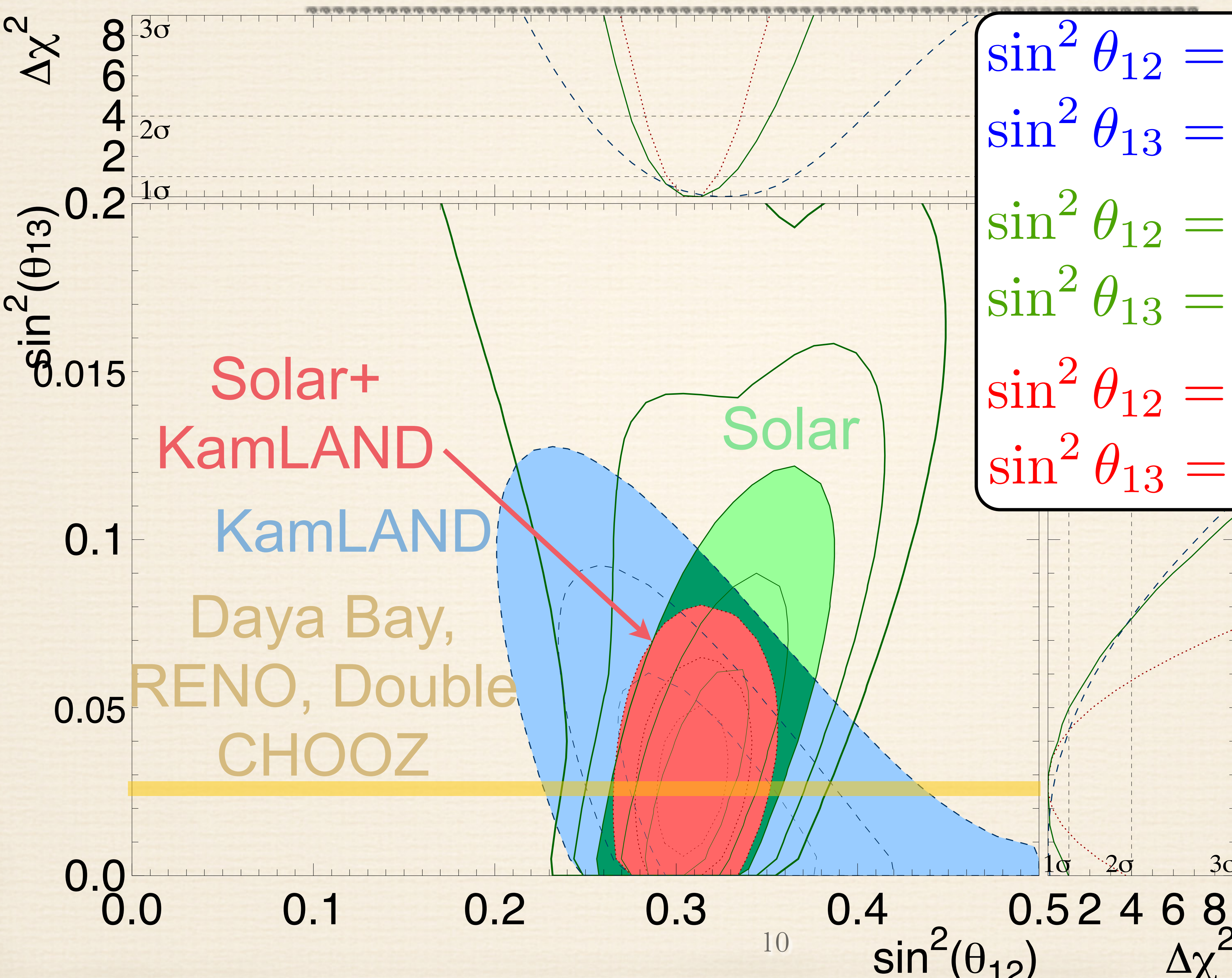
- solar ν measurements are important for understanding the sun (and stars); it is the only way to peak into the core of a star
- naïvely: since the coupling to W's/Z's of the neutrinos are known and measured, no particle physics at these low energies!
- however, since neutrinos mix and oscillate, there's flavor physics; one can use reactor data, but those are anti-neutrinos!
- also, solar ν's offer the opportunity to study weak physics in an otherwise untested environment of high matter density (not only inside the earth but also inside the sun)
- ν's may have additional, yet-unknown interactions: non-standard interactions (NSI)

Michael Smy, UC Irvine

Solar Neutrino Oscillations

- neutrino oscillations where first applied to solar ν's (as flavor oscillations) to explain, why R. Davis measured less ν's than predicted ("solar neutrino problem")
- matter effects (a resonance in the sun) where first applied to solve the solar neutrino problem with a small mixing angle
- solar neutrinos are sensitive to the angles θ_{12} and θ_{13} of the 3×3 neutrino mixing matrix (described by angles θ_{12}, θ_{13}, and θ_{23} and phase δ_{CP}) as well as one of the two mass^2 differences Δm^2_{21}
- solar ν data measures those parameters
- reactor data is more precise (except θ_{12}), but solar data is only from neutrinos, reactor data only from anti-neutrinos; different oscillation parameters would violate CPT invariance

Solar Neutrino Mixing Angles

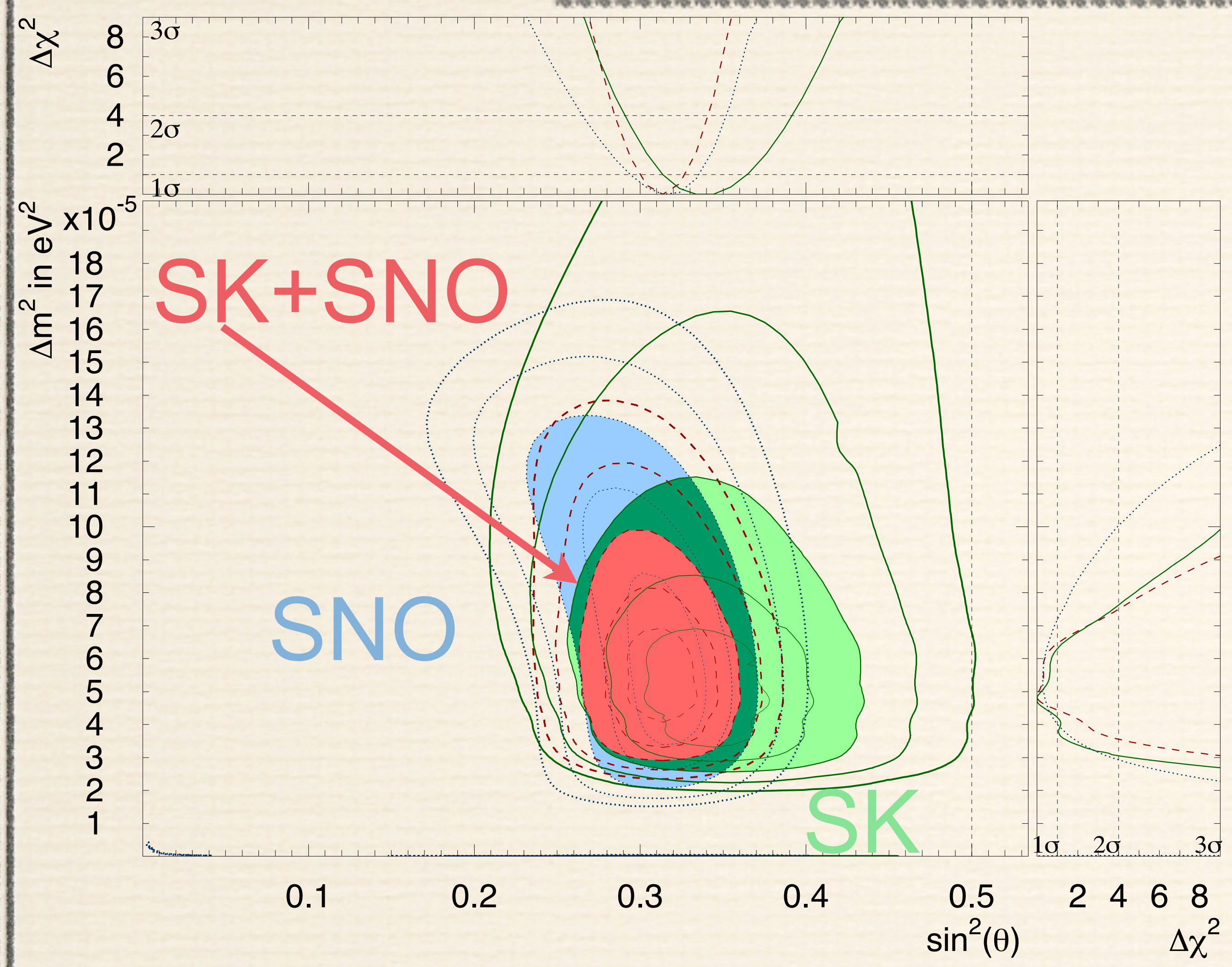


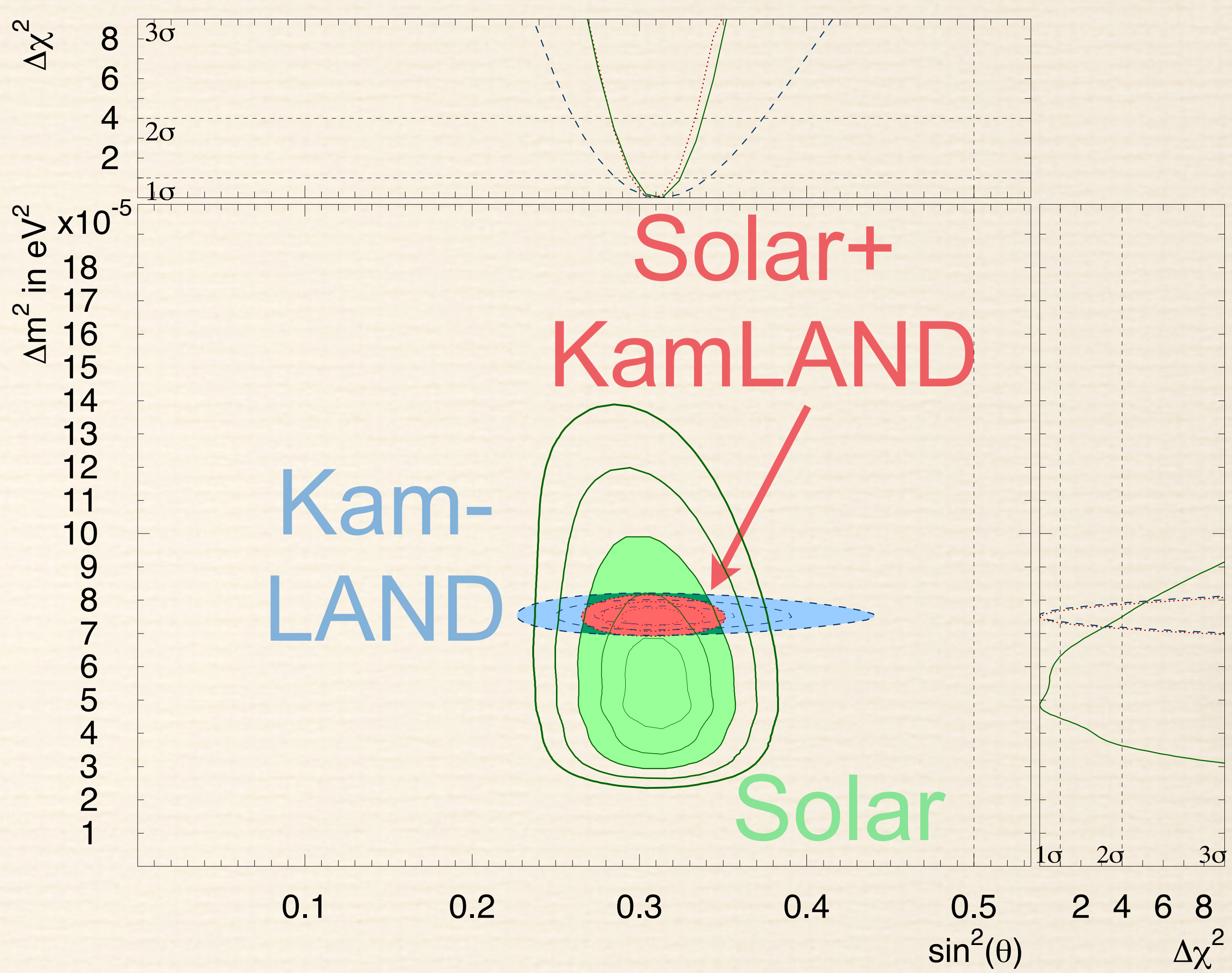
$$\sin^2\theta_{12} = 0.326^{+0.044}_{-0.037}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

$$\sin^2\theta_{12} = 0.310^{+0.021}_{-0.017}$$
$$\sin^2\theta_{13} = 0.027^{+0.024}_{-0.028}$$

$$\sin^2\theta_{12} = 0.309^{+0.014}_{-0.013}$$
$$\sin^2\theta_{13} = 0.027^{+0.016}_{-0.014}$$

θ_{12} and Δm^2_{21}: mostly ^{8}B Data





$\sin^2\theta_{12} = 0.317^{+0.017}_{-0.027}$ $\Delta m^2_{21} = 5.4^{+2.2}_{-1.1}$ $\times 10^{-5}$eV^2

$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$ $\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$ $\times 10^{-5}$eV^2

$\sin^2\theta_{12} = 0.313^{+0.014}_{-0.014}$ $\Delta m^2_{21} = 4.86^{+1.4}_{-0.62}\times 10^{-5}$eV^2

$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$ $\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$ $\times 10^{-5}$eV^2

$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$ $\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$ $\times 10^{-5}$eV^2

$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$ $\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}\times 10^{-5}$eV^2

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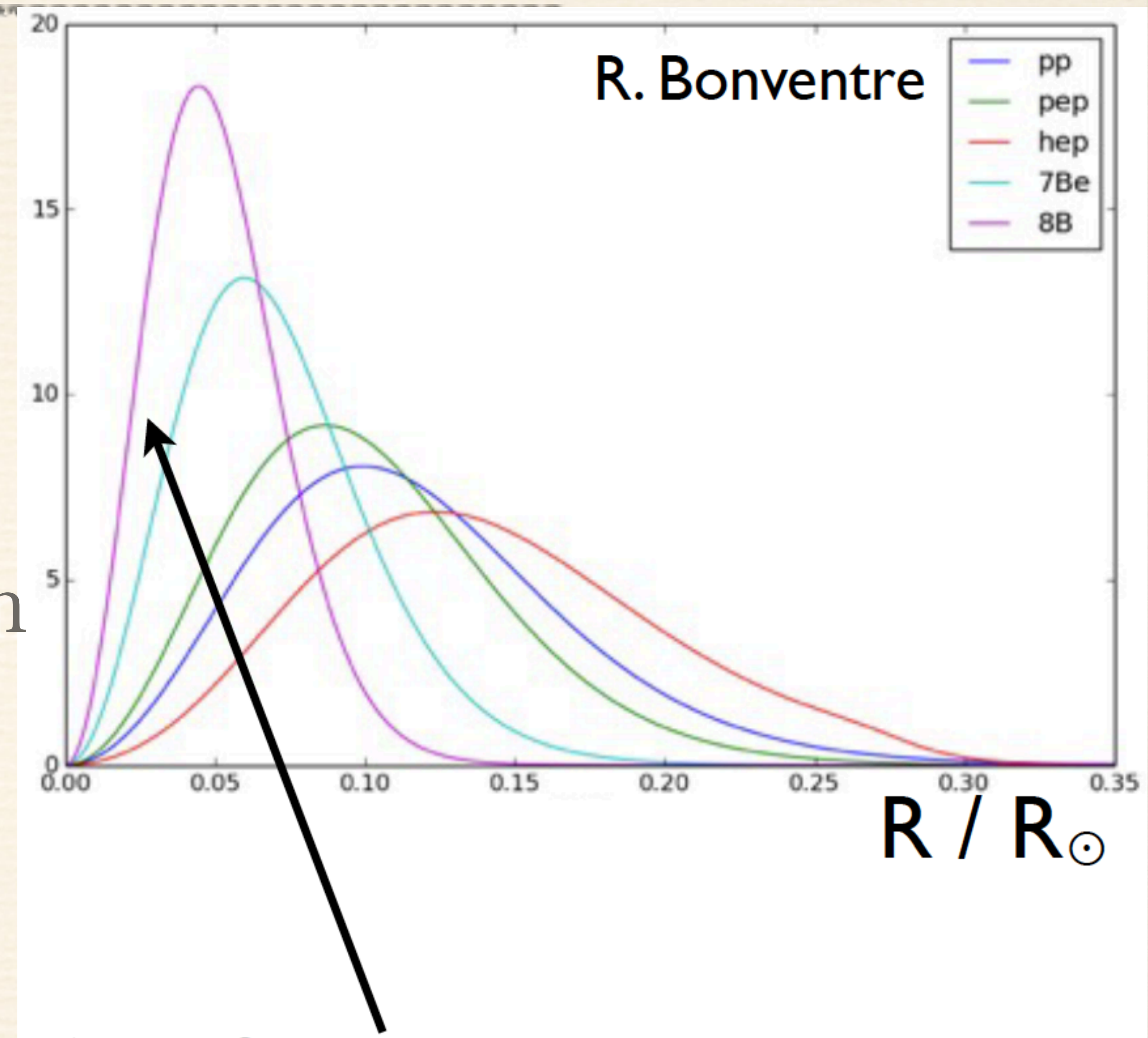
Why ^{8}B Data?

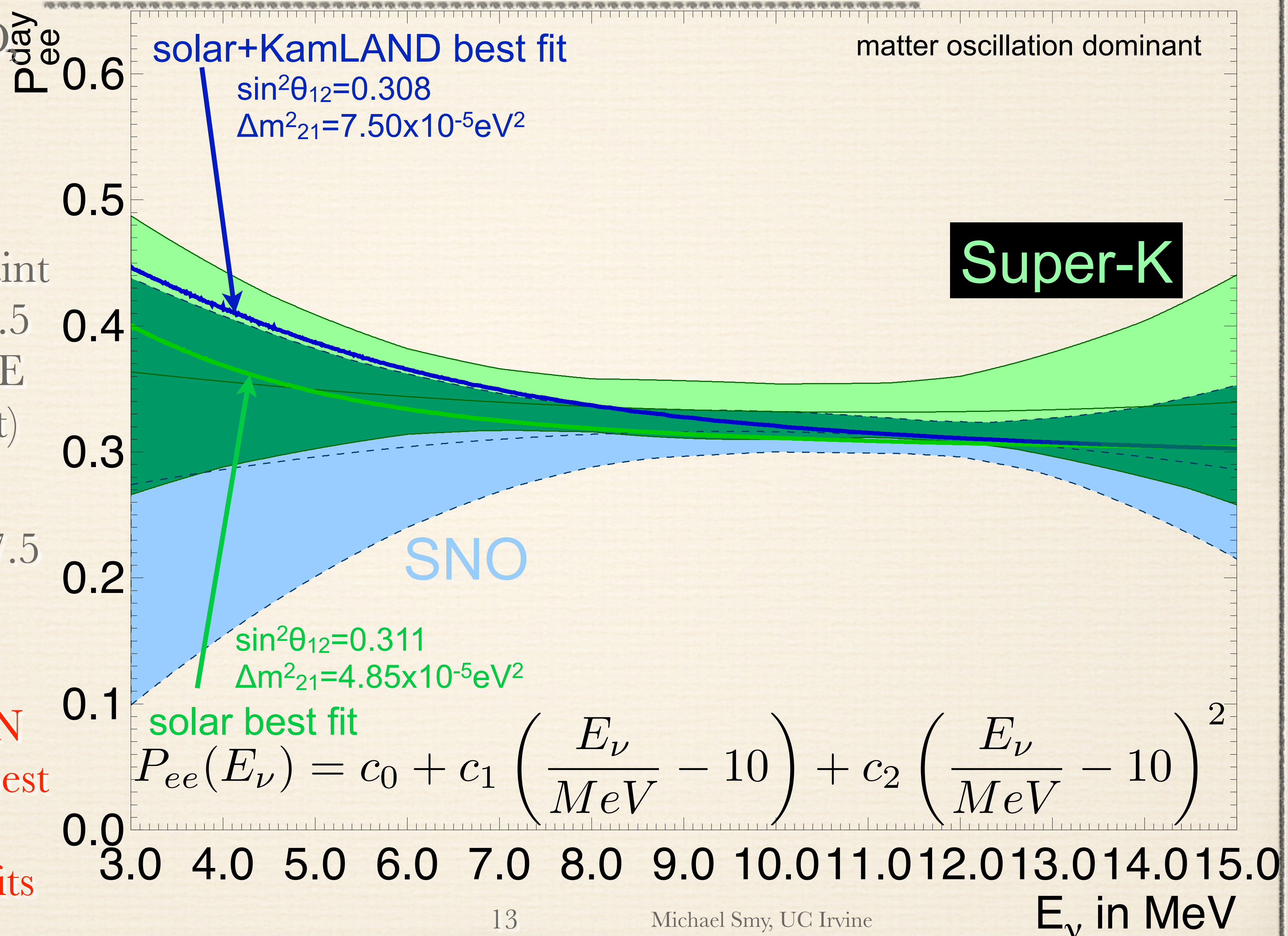
- Solar MSW Effect
- also best for testing MSW resonance:
  - already, SNO first showed, that vacuum oscillations can't explain data (P_{ee}<50% for extended energy range)
  - BOREXINO low energy measurements confirmed: P_{ee} is higher for low neutrino energy
  - ^{8}B neutrinos best for transition (edge of resonance)



^{8}B ν's are produced closest to the solar core ➛largest distortions of $P_{ee}(E\nu)$

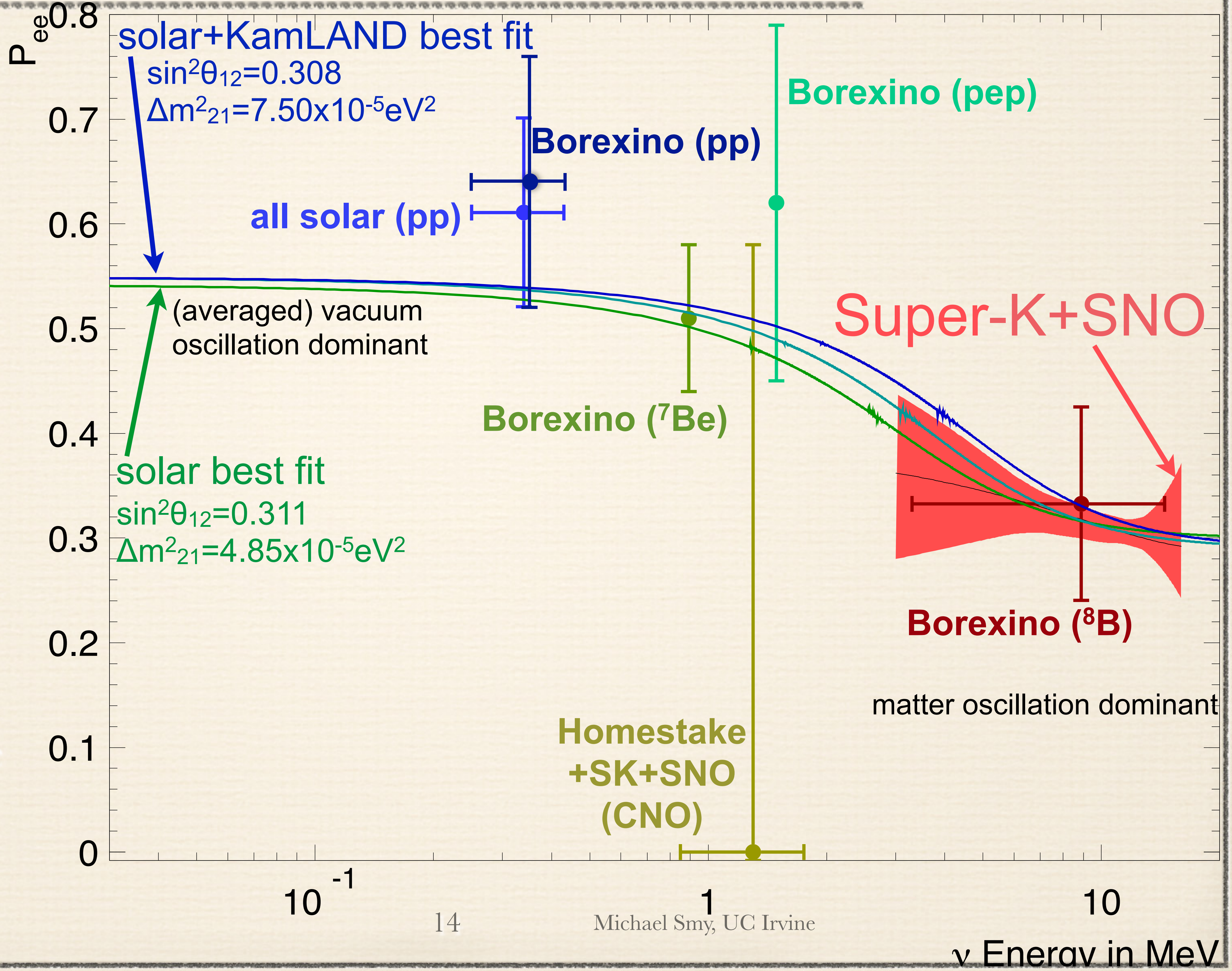
Present ^{8}B Solar Neutrino P_{ee} Data

- BOREXINO, KamLAND detectors too small: ignore
- SNO constraint stronger >11.5 MeV (better E measurement)
- SK stronger constraint <7.5 MeV (lower threshold)
- use fixed D/N value (solar best fit Δm^2_{21}) for SK & SNO fits



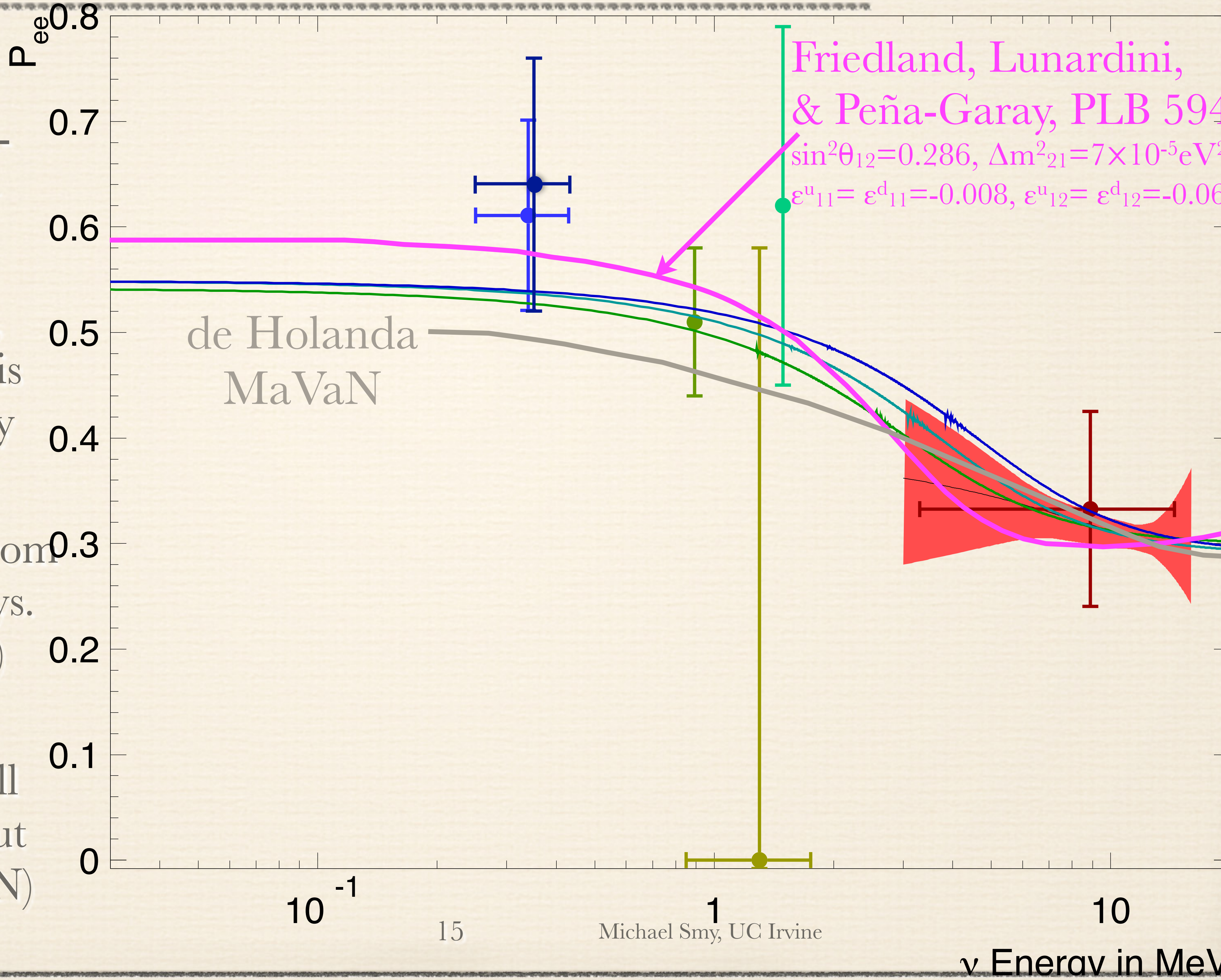
^{8}B P_{ee} and Other Solar ν Data

- other solar data shows that some energy dependence of P_{ee} must exist
- new pp data does not change "picture"
- solar matter effect evidence still indirect: no "smoking gun" that MSW is the only relevant culprit



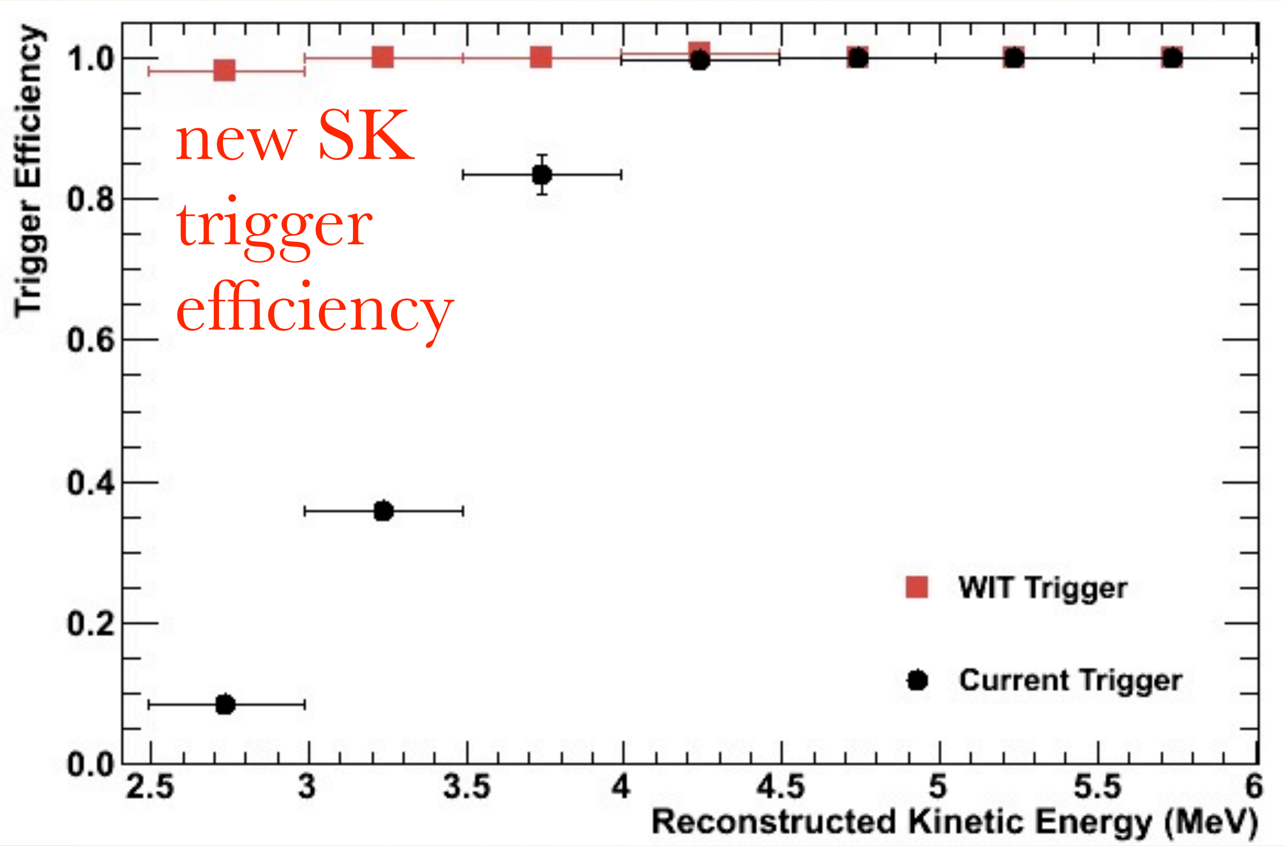
Non-Standard Interactions

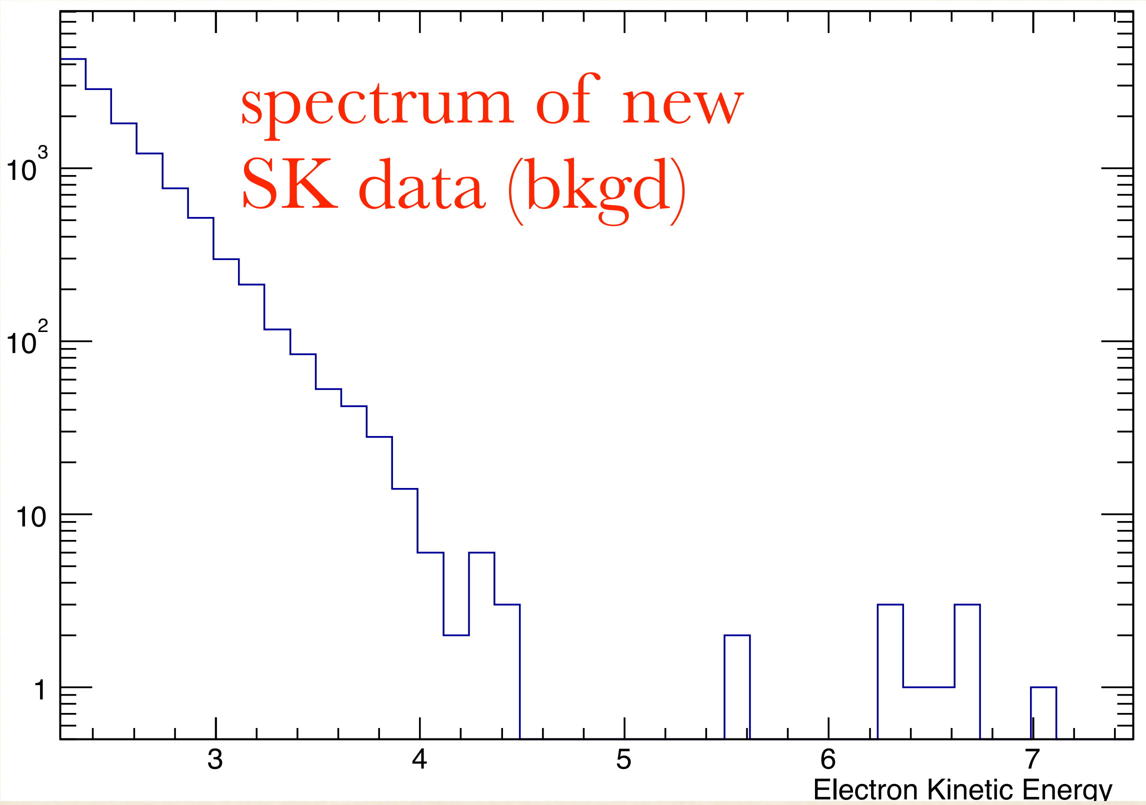
- NSI curve from Friedland, Lunardini, Peña-Garay, PRB 594 (2004)
- θ_{12} is a bit small, but otherwise this curve fit similarly well
- MaVaN curve from de Holanda, Phys. Scr. T127 (2006)
- parameters also outdated, but still reasonable fit (but excluded by D/N)



^{8}B P_{ee} (Near-Term)

- alas, no more SNO data
- BOREXINO, KamLAND too small for ^{8}B
- however: more Super-K data; perhaps with lower threshold
- sensitivity ~2-3σ (but so far, results are in the middle between energy-independent P_{ee} and MSW resonance curve)





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MSW-Vacuum Transition(Longer Term)

- new SNO+ ^{8}B data (medium term) 
  - detector is small for elastic scattering with ^{8}B ν's, but very deep
  - …but they will "pollute" detector with Te soon
- SNO+ CNO data might resolve it
- more BOREXINO data (improve uncertainties of low energy solar neutrino data to compare against)
- Theia (long-term) could trace resonance curve with large precision using charged-current interactions
- JinPing plans for $>5\sigma$ sensitivity from CNO data

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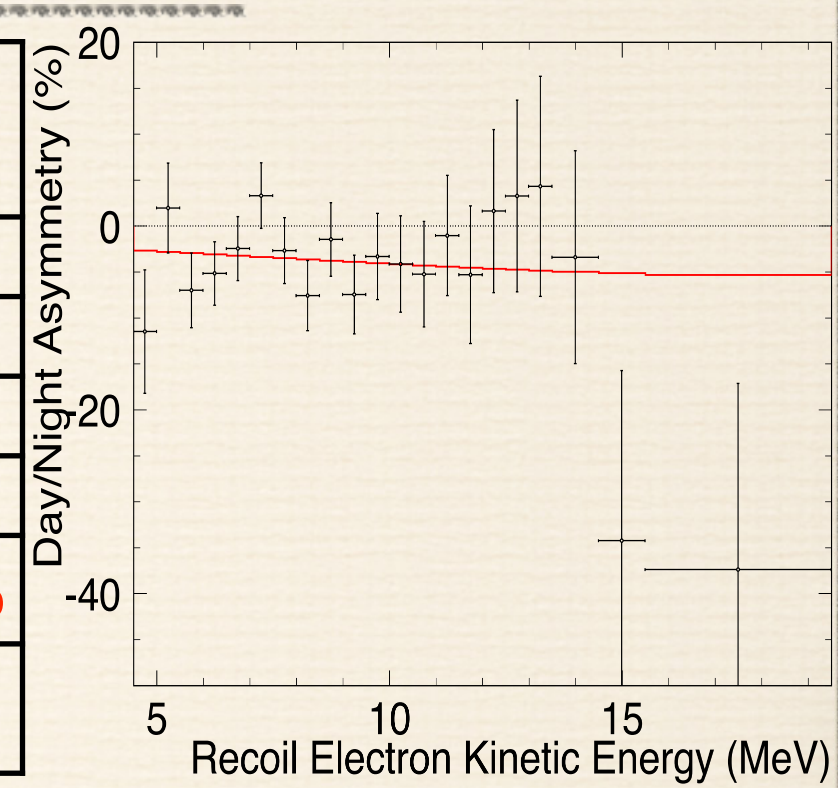
Day/Night Effect

- direct test of matter effects: compare flavor content of the same "beam" with and without matter being present

- with current parameters: no effect below few MeV; large effect near ~50 MeV, a few % for ^{8}B neutrinos
- form asymmetry $A_{DN}=2(D-N)/(D+N)$
- mostly a "regeneration" effect: $P_{ee}^{night}>P_{ee}^{day}$ $(A<0)$
- searched for by Super-K, SNO (E_ν>few MeV) and BOREXINO ($E_\nu \approx$few MeV): A_{DN} from SNO, BOREXINO agrees with zero
- 2.8σ indication of a non-zero A_{DN} from Super-K

Consistency of Day/Night Effect

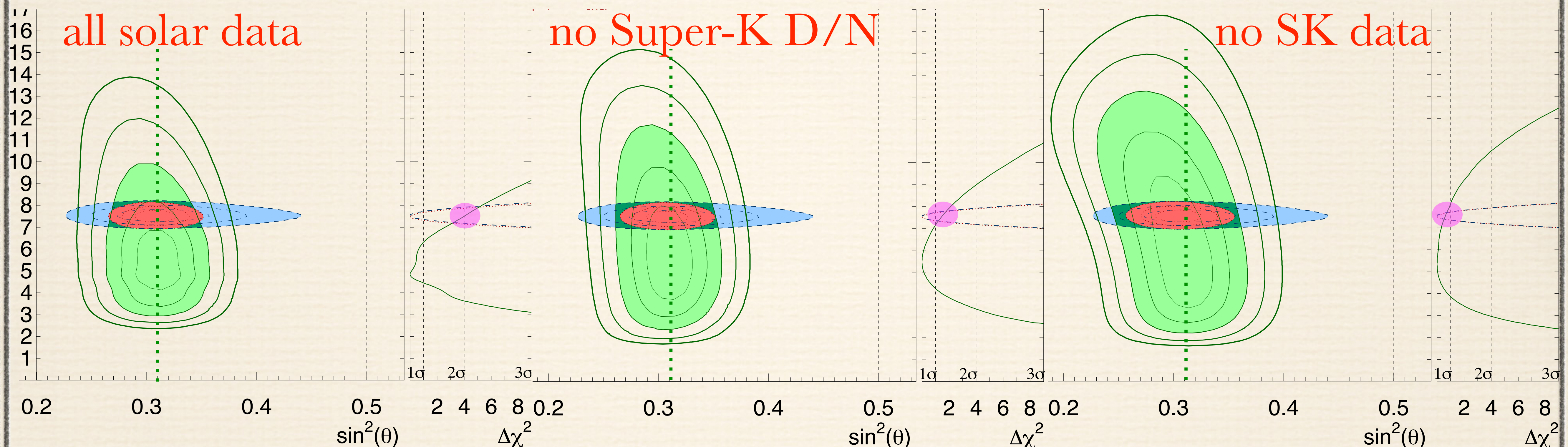
	Amplitude fit ($\sin^2\theta_{12}$=0.311, $\sin^2\theta_{13}$=0.025)		separate D, N:
	Δm^2_{21}=4.84x10^{-5} eV^2	Δm^2_{21}=7.50x10^{-5} eV^2	(D-N)/((D+N)/2)
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
comb	**-3.3±1.0±0.5%**	**-3.1±1.0±0.5%**	**-4.1±1.2±0.8%**
non-zero signif.	3.0σ	2.8σ	2.8σ



- Super-K-I value is a bit low (but only ~1σ)
- in general, good agreement within just statistical uncertainty
- consistent with SNO: equivalent SK A_{DN} is -2.0±1.8%
- (BOREXINO does not contradict due to lower ν energy)
- recoil e^- energy dependence as expected (from LMA)

$A_{DN}\neq 0$. So what?

- test CPT by comparing reactor $\bar{\nu}$ Pee with solar ν Pee
- so far, consistent with a ~2σ tension ($\Delta\chi^2$ is about 4)



- Super-K D/N data contribute about 2.5 to solar $\Delta\chi^2$
- Super-K spectral data contribute about one, other solar data contribute about 0.5 to this tension

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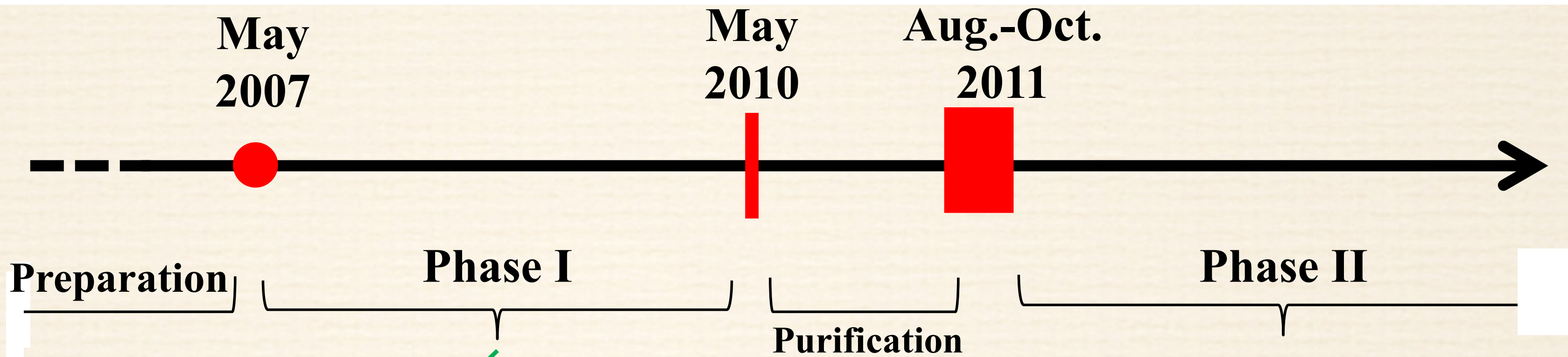
Future of Day/Night Data

- need ^8B ν data, threshold can be high
- Super-K should reach 3σ for $A_{DN}\neq0$ in the near term
- Super-K is too small for 5σ
- Hyper-K could do that, if it is deep enough
- charged-current interactions in ELBNF could be interesting:
    - A_{DN} is more powerful (like SNO's)
    - high nuclear threshold is not a problem
    - detector is deep
    - need to trigger on ~5 MeV electrons+de-excitation γ's
    - need big detector (at least 34 kton)
    - ^{39}Ar might be a show-stopper

BOREXINO Phase II

Borexino timeline



Planned end of phase II December 2014
Followed by a new calibration campaign

Measurement of the pp flux currently in progress with Phase-II data. Stay tuned!

Phase I:

- **(First) solar ^{7}Be-ν measurement**
- **^{7}Be-ν day-night asymmetry**
- **Low-threshold ^{8}B-ν**
- **First pep-ν detection**
- **Best upper limit on CNO-ν**
- **^{7}Be-ν seasonal modulation**

- **Geo-ν observation at > 4σ (initial phase II data included)**

- **Muon seasonal variations**
- **Limits on rare processes**
- **Neutrons and other cosmogenics**

Phase II:

- Measurement of pp-ν flux new milestone towards the full solar-ν spectroscopy
- New round of the previous measurements with improved precision
- Short-baseline ν oscillation: SOX
- With further purification : Measurement of CNO-ν flux (beyond phase II)

BOREXINO Phase II

Perspectives for phase II

Further possible achievements based on improved **backgrounds** after the purification

Th< 9 10^{-19} g/g 95% C.L.
U < 8 10^{-20} g/g 95% C.L.
Kr< 7.1 cpd/100 tons 95% C.L.

Purification (water extraction and nitrogen stripping) astonishingly effective in further reducing the already ultralow background!! Evaluated through the delayed coincidence tag

^{210}Bi=25.5 +- 1.8 cpd/100t

^{210}Po = 97 +- 3 cpd/100 t

Only residual backgrounds

Po210 factor 100 less than at the beginning of data taking

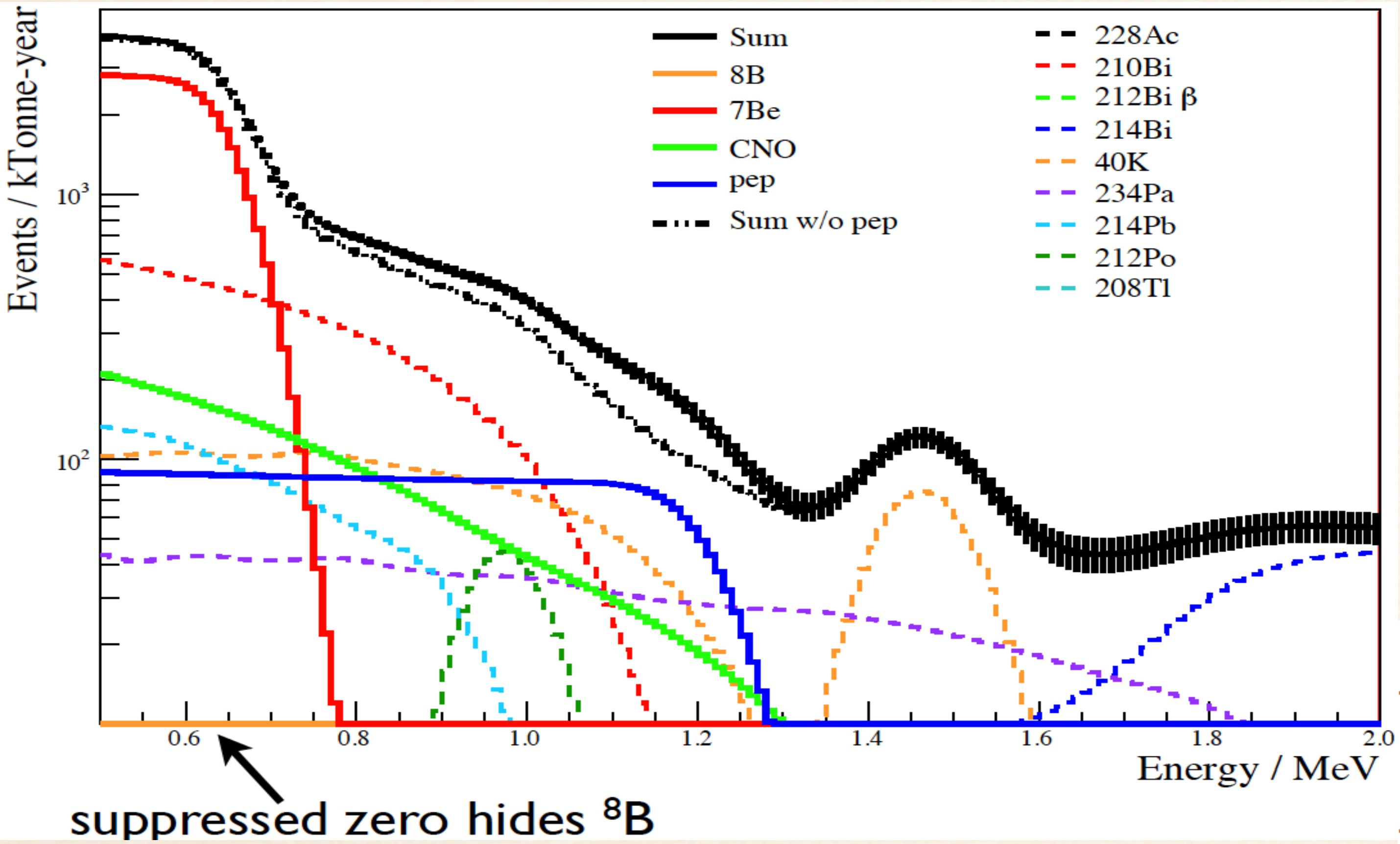
^{210}Bismuth (**the most relevant)** factor 2 less than in phase I

Improved ^{7}Be, ^{8}B, and pep →More stringent test of the profile of the Pee survival probability →sub-leading effect in addition to MSW, new physics, NSI?

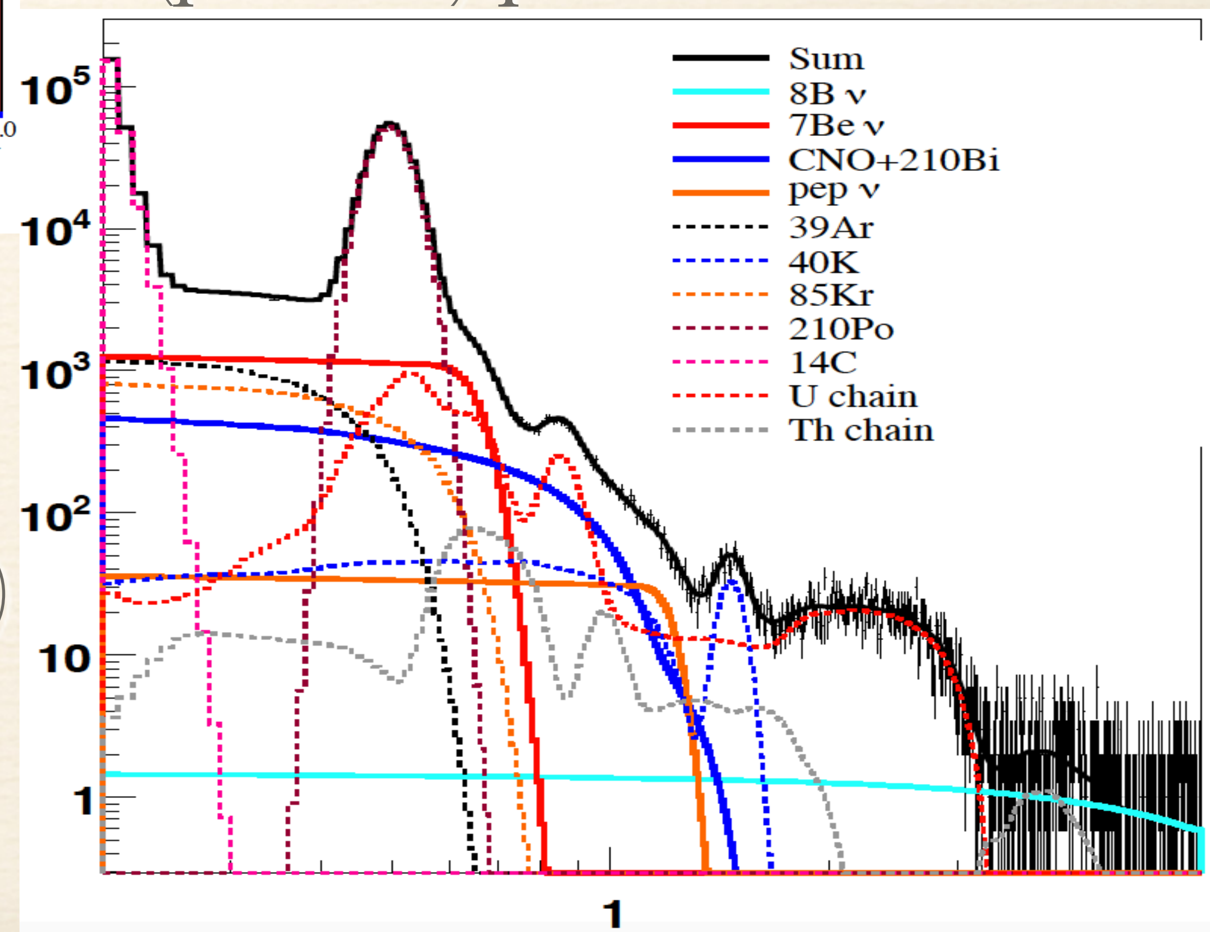
Improved ^{7}Be → some hint about metallicity?

CNO is the ideal metallicity discriminator → **more purification !** beyond the present phase II **^{210}Bi is the challenge**

Future Solar Experiment: SNO+



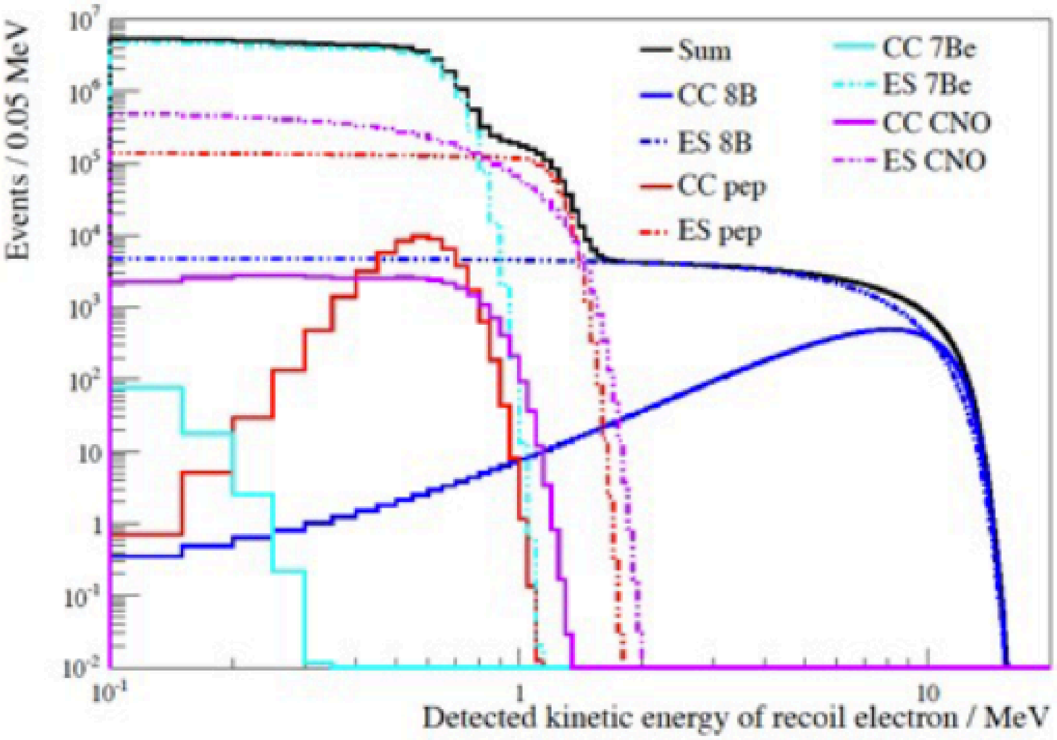
- deep (6080 mwe): less ^{11}C
- 1 year livetime, 50% FV (negligible external bkgd)
- assume BOREXINO (phase I) purification levels



- <3% ^{7}Be in 2 years
- <7% pep
- Few % on pp (dependent on ^{14}C)
- 15% on CNO
- Shape of 8B Spectrum

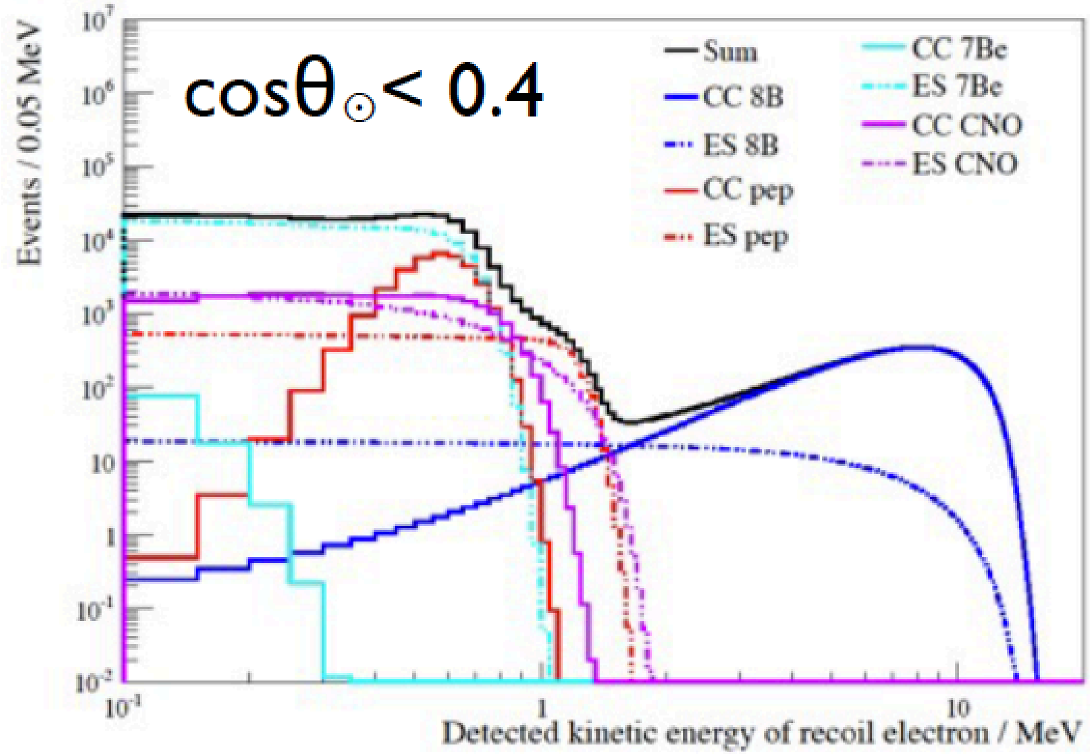
Future Solar Experiment: Theia

Unprecedented low-energy statistics (ES)



30kt fiducial
1% ^{7}Li by mass
100 pe/MeV

Spectral Sensitivity (CC)

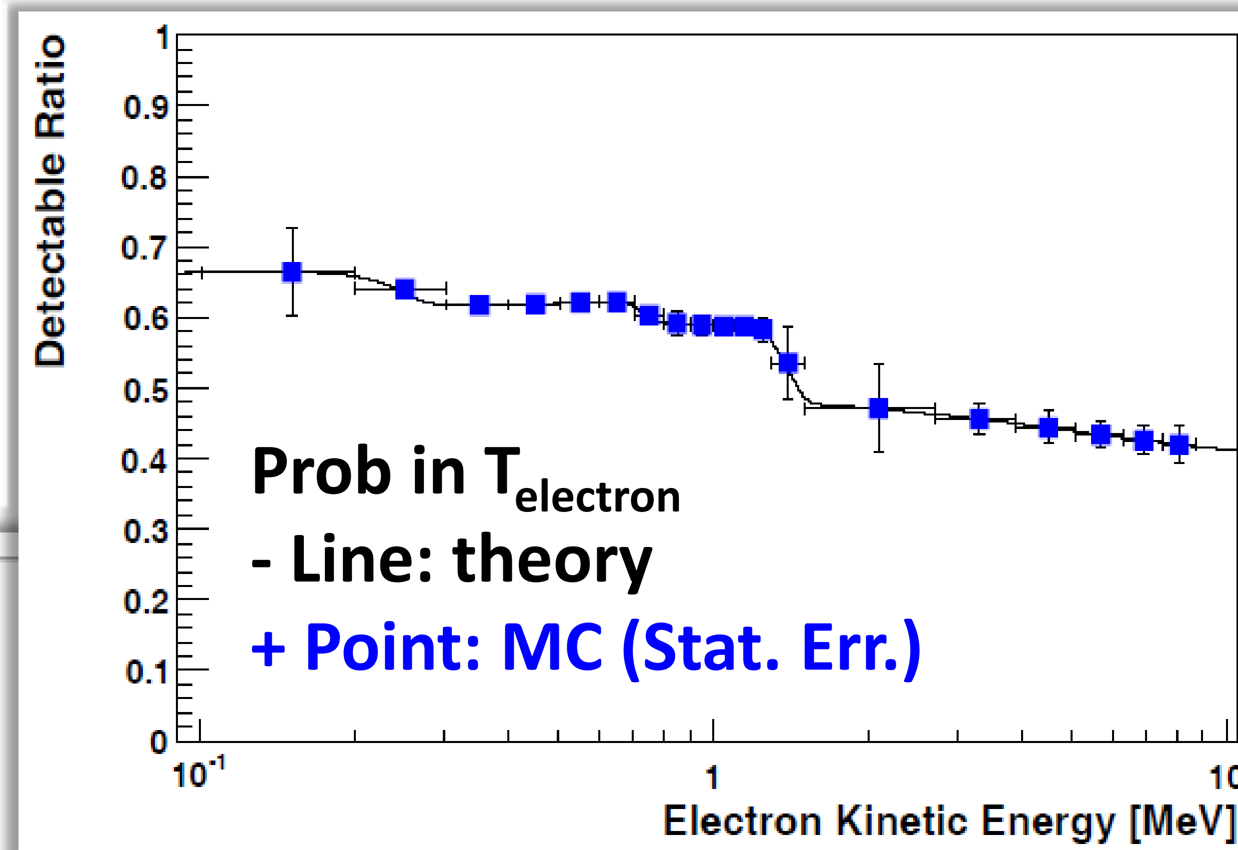


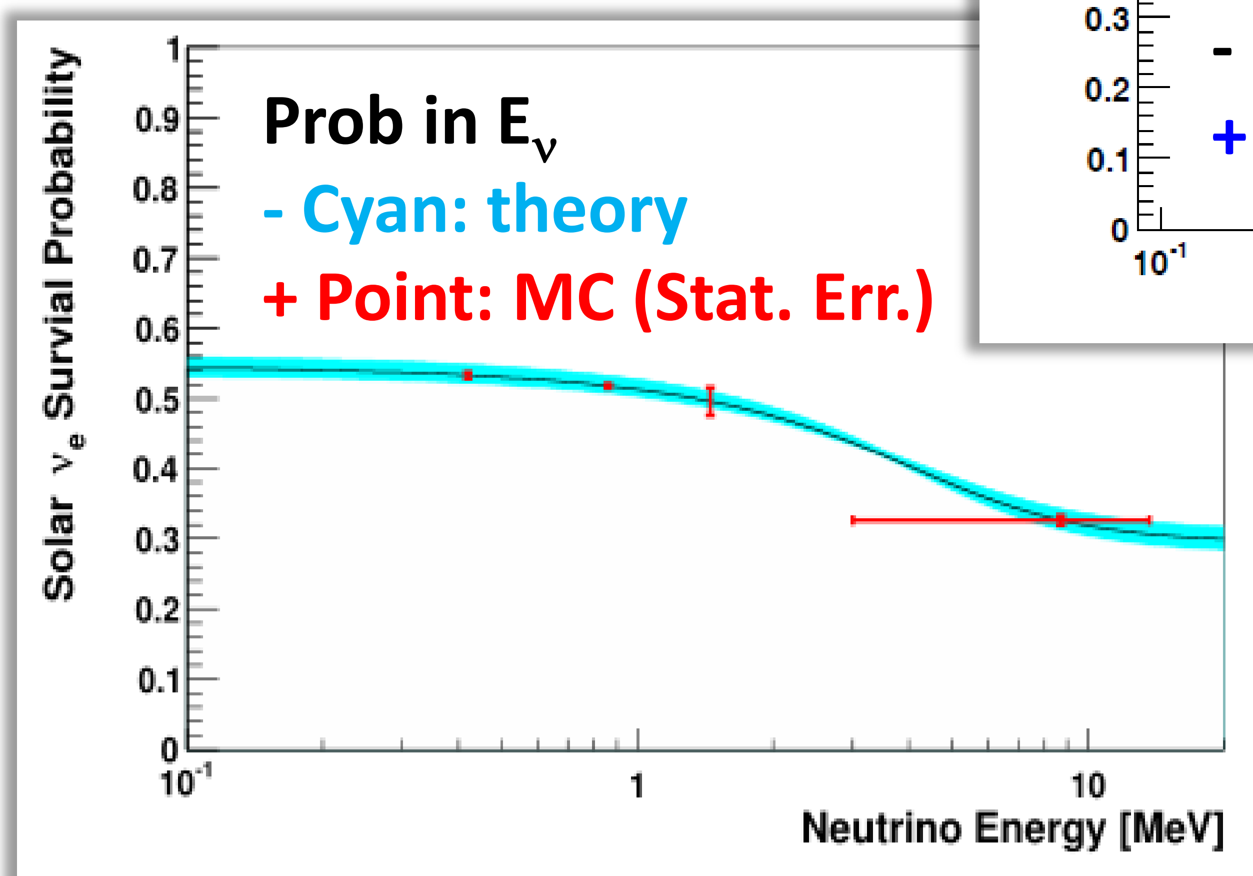
- 50-100 kton WbLS (→M. Yeh)
- high coverage with LAPPD's (→M. Wetstein)
- 4,800 mwe underground
- ^{7}Li enhanced

- high precision ^{8}B (MSW and Day/night)
- high precision pep
- separation of CNO components!

Future Solar Experiment in JinPing

- very deep: 6720 mwe
- ~1kton liquid scintillator (500 pe/MeV)





- trace MSW resonance
- discover CNO
- measure pp, ^{7}Be and pep fluxes

Shaomin Chen & Zhe Wang, Tsinghua University, for WINP, Feb. 2015

Conclusion

- amazing progress of solar neutrino understanding in the last 15 years
- we now monitor four out of the eight nuclear reactions with neutrinos
- understand solar neutrino flavor conversions: convincing indirect evidence for solar matter effects
- emergence of terrestrial matter effects
- still need proof for nature of solar resonance
- still need CNO fluxes to complete the picture
- would like low energy CC data (LENS)

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